Concerning the Influenced of Velocity Ratio and Topography Model on the Result of Rockfall Simulation

T. SHIMAUCHI[1,*], K. NAKAMURA[2], S. NISHIYAMA[3] AND Y. OHNISHI[3]

[1]*Meiji-Consultants Co .Ltd Saitama 333-0801, Japan*
[2]*A Depertment of Civil Engineering, Factory of Engineering, Tottori University, Tottori, Japan*
[3]*Depertment of Urban and Environmental Engineering, Kyoto University, Kyoto, Japan*

1. Introduction

Rockfall is one of the major hazards in rock slope cut for highways and railways in the mountainous area of Japan. In order to prevent the rockfall disasters, it is necessary to evaluate the influences on the preservation object in advance. The rockfall simulation is thus applied for the evaluation. However the behaviours of rockfall are complicated and uncertain phenomena, exhibiting a great deviation due to the influences of the scale and shape of falling rocks, the geographic feature of falling route and the roughness of the slope surface. Therefore input parameters and the deviation of the topographic model are given to take account of these uncertain factors. However at the present stage, the relationship between the given deviation and the rockfall behaviours is still not clear.

On the other hand, we have investigated a method to predict the velocity ratio(R_v) during the rockfall restitution time by using the DDAball.[1,2] However the rockfall behaviours as a whole, particularly the reproducibility of the trajectory, the reproducibility of rockfall velocity and the improvement of prediction accuracy have still not been realized.

In this paper, based upon the previous results, the essential factors for the reproducibility of velocity and trajectory were investigated through the reproductive analysis of the previous field experimental results.

2. Summary of Previous Field Experiments for Investigation

The field used in this investigation is located in Takamatsu of Japan where the former Ministry of Construction has performed the field experiment in 1980.[3] (it is designated as the Takamatsu Experiment in the following parts of this paper).

In the Takamatsu Experiment as shown in Fig. 1, one rock was allowed to drop from a height of 9 m , i. e., from two points with the inclination of 60° (A) and that of 30°(B). The trajectory and velocity of the falling rock on the slope were measured. The slope surface of the falling point was that of the shotcrete and the slope surfaces from the middle to lower part were the rock plate. The diameters of the falling rock were from 0.09 to 1.15 m and their average weight was 170 kg of the granite rock.

Figure 1 is for the B point, i.e., the trajectory recorded figure of the falling rock on the slope surface with the inclination of 30°. The velocity shows the right side with this figure Furthermore, in Table 1, the velocity ratio of the normal direction measured in the A and B points, and the conversed velocity ratio based on this value were shown in Table 1. In this paper, the velocity and trajectory concerning the measured example in the point of B were investigated.

*Corresponding author. E-mail: shimauchi-t@meicon.co.jp

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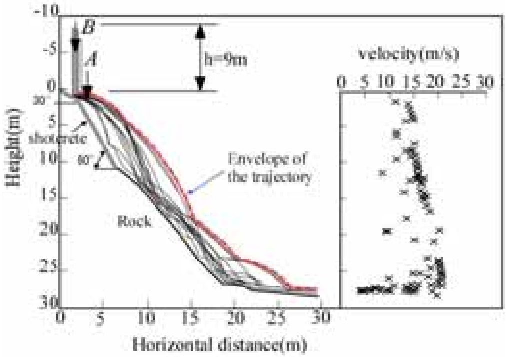

Figure 1. The Trajectory section and velocity of Takamatsu Experiment.

Table 1. The measurement result in Takamatsu Experiment.

Specimen	Incident Angle (°)	R_n	V_{out}	R_V(conversion)
A	60	0.49	7.8 ~ 9.4	0.59 ~ 0.73
B	30	0.26	3.6 ~ 5.2	0.27 ~ 0.29

Furthermore, the DDAball was used in this analysis. Oddball is the DDA taking part in the three dimensional rigid body elements, and is the program code characterizing the analysis of falling rock and rock block.[4]

3. Reproductive Simulation of Velocity

In the rockfall analysis, the velocity ratio (R_v) and the velocity ratio of the normal direction (R_n) are used as input parameters (Fig. 2 and Eqs. (1), (2)). However, these parameters have the property which decreases when the incident velocity of the normal direction increases.

$$Rv = \frac{V_{out}}{V_{in}} \tag{1}$$

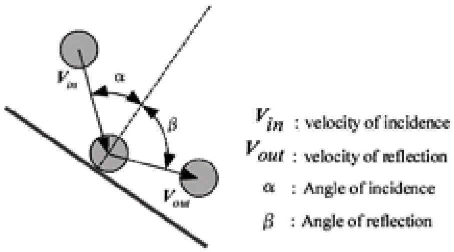

Figure 2. Properties of bouncing.

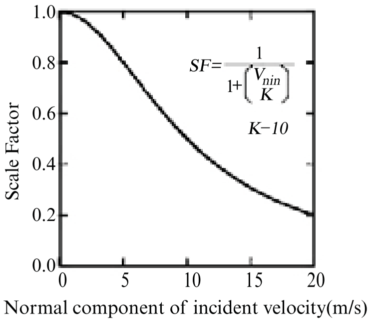

Figure 3. Scale Factor Curve was proposed considering to the velocity-dependency.

$$R_n = \frac{V_{out}\cos\beta}{V_{in}\cos\alpha} \tag{2}$$

Pfeiffer *et al.* (1989) proposed the Scale Factor Curve as shown in Fig. 3 and Eq. (3), with the purpose to consider the dependency of the incident velocity of the normal direction on the velocity ratio of the normal direction.[5] This curve may express the state that the velocity ratio of the normal direction will decrease greatly when the incident velocity of the normal direction increases. Its characteristic is its high adaptability in comparison with the curve of exponential function or other regression curves. This value is actually 0.0 ∼ 1.0. K of SF in Eq. (3) is designated as the revised velocity, expressing the gradient of the curve. The reflective velocity may be obtained from Eq. (4) by using the SF curve.

$$SF = \frac{1}{1 + \left(\frac{V_{n\,in}}{K}\right)} \tag{3}$$

$$V_{n\,out} = R_n(scaled) \times SF \times V_{n\,in} \tag{4}$$

$$V_{out} = R_V(scaled) \times SF \times V_{in} \tag{5}$$

On the other hand, we have clarified that the velocity ratio (R_v) has also the dependent property on the incident velocity of the normal direction, based on the laboratory experimental results of dropping a quartz ball on the reflective plate of rock and wood. We also showed that the Scale Factor Curve could be applied to R_v. In this case, the reflective velocity may be determined by Eq. (5).

Equations (4) and (5) show the reflective velocity of the normal direction and that the Scale Factor can be applied to either prediction method of the reflective velocity. However during the application, the velocity ratio of the normal direction and each property and characteristic of the velocity ratio should be taken into account.

Concerning the velocity ratio and the incident velocity of the normal direction, only the main points are mentioned in this paper.[2]

- The slower the incident velocity along the normal direction, the closer the velocity ratio approaches 1.0. The quicker it became, the velocity ratio reduced.
- The changing of velocity ratio is mainly due to the incident angle. The smaller the incident angle becomes, the closer R_v approaches 1.0. R_v will fall as the incident angle becomes larger.
- When the incident angle is the same, the quicker the incident velocity, the lower the velocity ratio will fall. Its influence is smaller than that of the incident angle.

- When the reflective plate is the rock plate (granite), the gradient of the SF curve is rather small, but for the soft wooden reflective plate, it becomes large (for the rock reflective plate, $K = 10 \sim 12$, for the wooden reflective plate, $K = 7 \sim 10$).

In the field, because the influences of the shape and state of rockfall as well as and the destruction of the ground, there exists a great deviation in the measured data. It is not simple like the laboratory experiment. However based on the above mentioned fundamental property, it can be considered that the velocity ratio is changing. Taking account of this property of the velocity ratio, we first test the reproducibility analysis of the previous Takamatsu Experiment.

Figure 4 is the plotting of the R_v (*conversion*) value of the Takamatsu Experiment as shown in Table1. This figure shows the SF curve connecting its minima In the coordinate, R_v *(scaled)* is designated in order to distinguish the measured velocity ratio and the velocity ratio of the Scale Factor Curve. The R_v (*conversion*) value shown here expressed the limits of the maximum and minimum caused by the reading errors of the incident angle against the incident velocity of the normal direction.

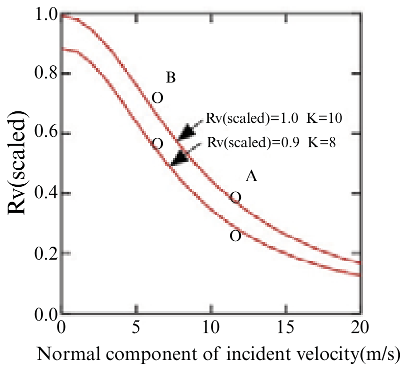

Figure 4. Takamatsu Experiment result and the SF curve.

Therefore, it can be considered that the SF curve itself may express the dependency of the incident velocity of the normal direction on the velocity ratio, taking account of the characteristic of the slope surface. Furthermore, it may also be considered that the two curves may express the range of roughness deviations due to the incident and reflective angles. Based upon this consideration, the iterative calculations have been performed in this investigation, taking $R_v(scaled) = 0.95$ and $K = 9.0$ as the mean value, giving the range of $R_v(scaled) = \pm 0.05$,, $K = \pm 1.0$ as the standard deviation. The iteration number was 100.

The results were shown in Fig. 5. In this figure, the trajectory obtained by the simulation were shown. This figure showed the envelope of the trajectory of Takamatsu Experiment (Fig. 1). At the first falling place immediately after the falling, as the falling rock reached the flat part in the lower side of the slope surface, the reason why the rock would not spring highly up was the effect considering the dependency of incident velocity of normal direction. Thus it may be considered that the velocity has been reproduced. However the trajectory have been focused on the narrow range of the restitution area, monotonously rising and the envelope of the Takamatsu Experiment greatly moved down. The main reason is considered to be the modelling of the even inclination region with a long straight line.

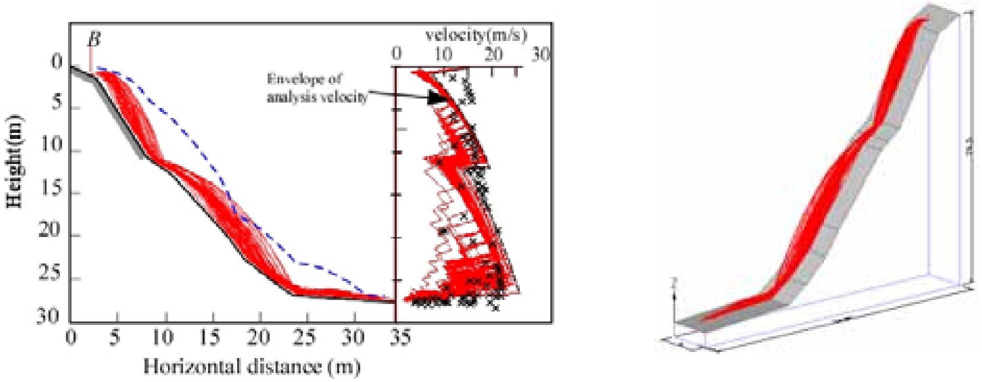

Figure 5. Analysis results considering the dependency of incident velocity of normal direction on velocity ratio.

4. Reproducibility Simulation of Trajectory

From the reproducibility analysis results of velocity, it is difficult to reproduce the trajectory by only considering the dependency of the incident velocity of the normal direction on the velocity ratio. In order to solve such problems of the trajectory, several methods have been proposed: one is to give deviations to the incident angle; the other is to give deviations to the topographic model itself. In this paper the second method was investigated.

The investigated model was the three dimensional topographic model as shown in the right side of Fig. 5. It is the model which had been pushed out 30 m in the y direction and divided the ground surface with one side being approximately 1.5 m of the triangle mesh. In this investigation, the normal distribution with mean value and standard deviation σ was given to each vertex of each triangle mesh with the height z(m). The topographic model with randomness was established. The number of these established model was 100. By using these models, the analysis had been performed by applying the scale factor curve as shown in Fig. 4.

In the Takamatsu Experiment, Komura or Ushiro *et al*. reported that the standard deviation of the incident angle on the concrete slope surface was $\sigma = \pm 11.22°$ by assuming that all the causes of deviation in the velocity ratio of the normal direction R_n was the reading errors of the inclination angle.[6,7] Based on this report, the average side length of the triangle elements composing the investigated model was determined as 1.8 m, and the variation in the upper and lower directions of the vertex $\sigma = \pm 0.18$ (m) (Fig. 6).

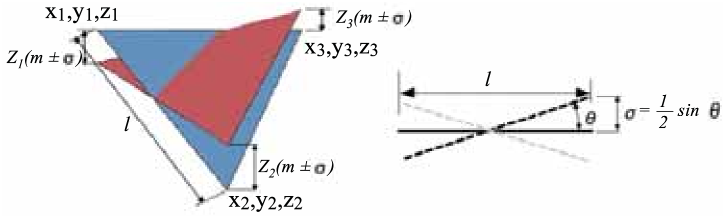

Figure 6. Input of height-deviation to triangle elements.

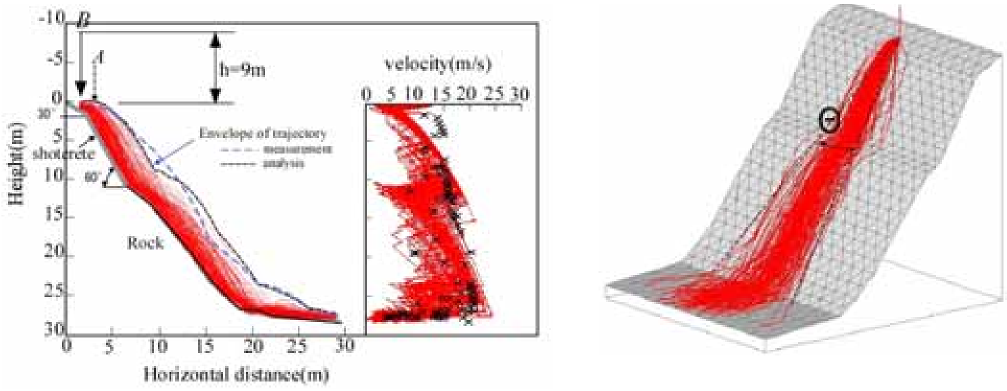

Figure 7. Input of height-deviation to triangle elements.

The analysis results were shown in Fig. 7. In this figure, we can see that there appeared a great variation in the trajectory and velocity, when the roughness of the topographic model was taken into consideration, in comparison with the case where only the velocity ratio deviations were taken into account. These effects were quite evident. Not mention the falling point, there appeared a new restitution section on the way of the long linear slope surface in the 2 ∼ 11 m height or 13 ∼ 20 m height. Thus the appearance of the cross-section of the trajectory and the velocity distribution were close to the experimental results.

On the other hand, it can be seen that the trajectory extended from the falling point when the roughness of the topographic model was taken into account in comparison with the three dimensional diagrams of Figs. 5 and 7. The relationship between the extension of the falling trajectory and the deviation given to the vertex height of the mesh were shown in Fig. 8, The deviation of the vertex height σ was increased from ±0.04 m to ±0.09 m, ±0.18 m, ±0.24 m, that is, the larger the roughness of the slope surface becomes, the farther extended the rockfall trajectory. Komura *et al.* reported that the extension from the falling point was about 30° in the Takamatsu Experiment.[6] In addition, Komura *et al.*, determined the roughness based upon the measured results of the deviation in the incident angle, the extension angle from the falling point was also 30°. It was fairly in agreement with the Takamatsu Experimental

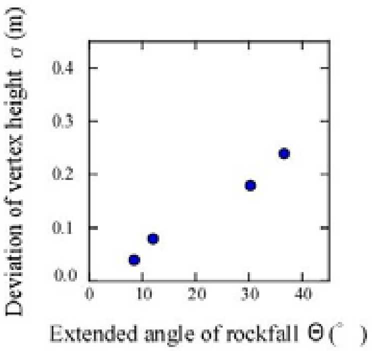

Figure 8. Relationship between deviation of vertex height considering triangle element and extending angle of rockfall.

results. From these results, we may consider that the method of this investigation, which gives deviations to the small roughness of the topographic model and the method which gives deviation to the incident angle and the mass point analysis performed by Komura *et al*. and Ushiro *et al*. have approximately the equivalent effects of improvement on the trajectory.

5. Conclusions

Concerning the rockfall experimental results performed by the former Mimistry of Construction in Takamatsu of Japan (1989), a reproducing experiment was carried out by using DDAball.

The reproducibility experiment was performed by two steps. At the first, the deviation effects of the dependency on the incident velocity of the normal direction was investigated by using the model expressing the even inclination region with a long straight line. The results were shown as follows:

(1) There is a dependency of the incident velocity of the normal direction on the velocity ratio. It is important to consider this property for the reproducibility of velocity.
(2) In order to consider the deviation of the trajectory, it is important to take account of the small roughness in the topographic model, the more roughness in the model, the greater the scattering of the trajectory will become.

Naturally, in the practical rockfall simulation, it is necessary to consider both (1) and (2). However, in order to elevate the reliability of the rockfall simulation, it is necessary to clarify hereafter the determination method of the factor corresponding to the field conditions such as the bare rock or the soil and sand, the measuring method of roughness and the method reflecting the analysis mesh etc.

Moreover, although it does not mention in this paper, the occurring place of rockfall, the influence of the initial velocity on the results are unexpectedly very important. In the future, it is necessary to investigate the shape of rockfall, the influence of trees and the adequacy of the probability distribution.

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